The Discovery of a Hyperluminal Source in the Radio Afterglow of GRB 030329

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ABSTRACT

Taylor, Frail, Berger and Kulkarni have made precise VLBI measurements of the size and position of the source of the radio afterglow of GRB 030329. They report a size evolution compatible with standard fireball models, proper motion limits inconsistent with the cannonball model, and a double source, i.e. "an additional compact component" on day 51 after the GRB, totally unexpected in the standard models. We outline a consistent interpretation of the ensemble of the data in the realm of the cannonball model. The observed double source is a radio image of the two cannonballs required in this model to explain the γ-ray and optical light curves of this GRB; their separation agrees with the expectation. Thus interpreted, the observation of the two sources —separated by a "hyperluminal" distance— is a major discovery in astrophysics: it pins down the origin of GRBs.

Subject headings: gamma rays: bursts

1. Motivation

The currently best-studied theories of Gamma-Ray Bursts (GRBs) and their afterglows (AGs) are the *Fireball* models (see, e.g., Zhang & Meszaros 2003 for a recent review) and the *Cannonball* (CB) model (see, e.g., Dar & De Rújula 2003a; Dado, Dar & De Rújula, 2002; 2003a and references therein). The first set of models is often considered to be *the standard model* of GRBs. The Standard and CB models are different in their original basic hypotheses, in their description of the data, and in their predictions.

The CB model (Dar & De Rújula 2000, 2003a) is based on the assumption that GRBs and their afterglow (AG) are produced by superluminal CBs (plasmoids made of ordinary

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matter) ejected in the explosions of supernovae (SNe). The predicted *bulk motion* of the CBs of GRBs is so fast —in comparison to that of quasar or microquasar ejecta— that we have dubbed it *"hyperluminal"* (Dado, Dar & De Rújula, 2003a). Superluminal motions of moving astronomical objects in the plane of the sky were first discussed —in exquisite detail and with 19th-century elegance— by Courdec (1939). Following the discovery of the very bright GRB 030329, at a nearby $z = 0.1685$, we previously studied the radio-detectability of the hyperluminal motion of its ejecta (Dado, Dar & De Rújula 2004, hereafter DDD).

Taylor, Frail, Berger and Kulkarni (Taylor et al. 2004, hereafter TFBK) have recently published their VLBI observations of the radio AG of GRB 030329. They report that *"In observations taken 51 days after the burst we detect an additional compact component at a distance from the main component of 0.28 ± 0.05 mas (0.80 pc). The presence of this component is not expected from the standard model"*. TFBK argue that the CB model is also inconsistent with their observations. We propose an interpretation of the data in which that is not the case. The gist of our interpretation is simple: as we argued in DDD, there are *two* sources relevant to the radio AG: the *two* CBs responsible for the observed *two-pulse* γ-ray fluence and the observed *two-shoulder* optical AG. The superluminal motions of the two sources have apparent displacements that differ in magnitude (DDD). TFBK's double radio source (whose significance is larger than 20σ) is seen when the two CBs have similar fluences at 15.3 GHz. At other times and frequencies the two contributions have not been clearly resolved. This is not so surprising: the R-band non-SN contribution to the AG (i.e. one of the CBs) has been seen to rebrighten at a date coincident with the double-source observation (Matheson et al. 2003). Compact objects associated with a core-collapse supernova have been resolved once before, in SN1987A (Nisenson & Papaliolios 1999). In our interpretation these objects were also CBs emitted in opposite directions. Neither of them was pointing accurately enough towards the Earth for its induced GRB to be observable.

2. Summary of the relevant data

TFBK have localized the radio AG of GRB 030329, with a precision of 0.2 mas, at various radio frequencies, and at times corresponding to approximately 3, 8, 25, 51 and 83 days after burst. At two epochs, TFBK report an observed angular size of the source: 0.065 ± 0.022 mas at 15.3 GHz and 0.077 ± 0.036 at 22.2 GHz on day 25, and 0.172 ± 0.043 mas at 8.4 GHz on day 87. The rest of the data yield only upper limits for this observable. These results are compatible with expectations of standard models.

More intriguingly, TFBK report that *"The Gaussian fits made to the measured visibility data as a function of baseline length returned residuals consistent with noise in all but one*

case. The fit to the 15 GHz observation on May 19 [day 51] *produces a significant residual (>20 sigma) which is ∼30% of the peak flux density and offset to the northeast at*

$$\Delta\alpha_{1,2} = 0.28 \pm 0.05 \text{ mas} \tag{1}$$

from the main component. The exact nature of this second component is not known but it would require an average velocity of 19c to reach its offset from the flux centroid."

Finally TFBK solve for proper motion, obtaining a limit on the angular displacement of *an assumed single source* during the duration of the observations:

$$\alpha[80\,\text{days}] = 0.10 \pm 0.14 \text{ mas} < 0.3 \text{ mas}. \tag{2}$$

It is relevant to our interpretation of the data that TFBK assumed a single source (§4 & §5).

3. A CB-model interpretation of the double-source separation

We identify TFBK's 20σ evidence for a double source as a radio image of the two CBs of GRB 030329. At the time of this observation, the **"faster" CB** has moved 0.28 ± 0.05 mas away from the **"slower" CB**, the motion of the latter being unobservably small during the whole duration of the campaign. We argue that this straightforward interpretation of the double source is compatible with the rest of the observations.

As shown in Fig. (1), the R-band optical AG of GRB 030329 was overtaken by the contribution of the associated SN at day ~ 10 after the explosion (Garnavich et al. 2003; Stanek et al. 2003), as expected (Dado, Dar & De Rújula, 2003b). The CB-model interpretation of this GRB (and, previously, that of GRB 021004; Dado, Dar & De Rújula, 2003c) requires contributions from two CBs, producing a two-pulse γ-ray fluence and a two-shoulder optical AG. The predicted motion of the faster CB (labelled CB2 in the figure) is larger than that of the slower CB, CB1 (DDD).

To a good approximation, and for observer's times t larger than a few days, the approximate time dependence of a CB's angular displacement and velocity are:

$$\alpha_{\rm CB}(t) \approx \frac{\theta}{D_A}\left[\frac{6\,x_\infty^2\,c\,t}{(1+z)}\right]^{1/3} \tag{3}$$

$$\dot\alpha_{\rm CB}(t) \approx \frac{\theta}{3\,D_A}\left[\frac{6\,x_\infty^2\,c}{t^2\,(1+z)}\right]^{1/3}, \tag{4}$$

where D_A is the angular distance, θ is the angle of the CB's motion relative to the line of sight, and x_∞ is a "deceleration parameter" (Dado, Dar & De Rújula, 2002). For an interstellar medium of constant baryon density, the above expressions are exact large-t limits.

The optical light curves of GRB 030329 are very finely structured, as can be seen in Fig. (1) for the case of the R-band data. In the CB model the sharp magnitude variations starting at various times after day 1.5 were interpreted and modelled in DDD as the result of density inhomogeneities that the faster CB encounters as it exits the superbubble in which its parent SN and many previous ones were immersed. The fits in DDD returned $\theta[1] \approx 2.2$ mrad and $\theta[2] \approx 2.3$ mrad for the angles of the two CBs. As the CBs cross the density inhomogeneities, the description of their deceleration is quite elaborate (DDD), but the overall results for their positions and velocities are still sufficiently well described by Eqs. (3,4), with "effective" parameters $x_\infty[1] \approx 0.017$ Mpc and $x_\infty[2] \approx 0.048$ Mpc.

The (elaborate) results for the predicted motion of the two CBs, relative to the first day of TFBK observations, are shown in Fig. (2a). The corresponding angular distance between the two CBs as a function of time is shown in Fig. (2b), along with the distance between the two sources, measured by TFBK on day 51.

The central value $\Delta_{1,2} = 0.28$ mas of Eq. (1) corresponds to a transverse distance of $d =$ 0.8 pc at the GRB's location. From Fig. (2a) one can read that, by day 51, the faster (slower) CB should have moved 0.70 mas (0.35 mas) away from the parent SN, corresponding to a transverse distance $d[2] = 2.0$ pc ($d[1] = 1.0$ pc). The distances along the CB's trajectories are $d[2]/\theta[2] \sim 0.87$ kpc and $d[1]/\theta[1] \sim 0.43$ kpc. The prediction of where a CB is —after travelling for hundreds of parsecs— is not trivial, particularly if the interstellar medium has the complicated density profile required in the CB model to explain the intricate optical AG light curves. A result that is correct to better than 2σ, as in Fig. (2b), is satisfactory.

4. CB-model interpretation of the rest of the data

The CBs emitted by microquasars are occasionally seen to "rebrighten", e.g. the western CB ejected, two years earlier, by XTE 1550-564 (Corbel et al. 2002). We have interpreted in DDD the measured observer's time, $t \sim 1.5$ d —when the optical light curves show a first fast rebrightening— as the time at which the faster CB reaches the stratified density profile at the boundary of the supperbubble. The calculated time at which the slower CB reaches the same position is $t \sim 13$ d. At that time the optical light curves are dominated by the SN contribution and the second CB's rebrightening is barely observable. Neither should the rebrightening be directly observable as a **sharp** effect in the radio light-curves: the radio emission is delayed and smoothed by the time it takes electrons to "cool down" to radio-emitting frequencies (Dado et al. 2003a, DDD). For these reasons, and because we have not developed the extremely laborious CB-model analysis of radio AGs in complicated density profiles, we did not pay attention in DDD to the putative consequences of radio

rebrightenings of the CBs, neither did we report the predictions for the motion of the slower CB and the distances between CBs, as we have now done in Fig. (2). With the benefit of hindsight, **these were oversights.**

A very relevant rebrightening is that seen by Matheson et al. (2003) in the R-band AG of GRB 030329, in observations beginning on day 51.75. They report a "jitter episode": *"Variations of $>$ 30% on timescales of $\sim$ 2 days more than 50 days after burst ... unlikely to be in the SN component, as such variations have never been observed in any other SN"*. The jitter is expected if one of the CBs is crossing new density inhomogeneities from day ~ 50 onwards. The rebrightening must be very intense, since at that time the SN would otherwise be expected to be very dominant, see Fig. (1), and Fig. (15) of Matheson et al. (2003).

To summarize: The faster CB crosses various density variations (mainly enhancements) on days 1.5 to 7. The slower CB is predicted to cross these enhancements and repeatedly rebrighten from days 13 to ~ 60. The faster CB reaches new enhancements starting at day ~ 50. Enhancements lead to rebrightenings, but the general trend of a fading fluence steepens after a rebrightening: the fluence is proportional to a high power of the CB's Lorentz factor, which diminishes fast while crossing the density enhancements (DDD). To accommodate the double source observed by TFBK, it must be that the faster CB has rebrightened, by day 51, to 30% of the total radio signal at 15.3 GHz, fading fast thereafter. This radio rebrightening and fading are expected, given the large optical "jitter" observed at very similar times.

How do we reconcile the observation of a double source at a single frequency and a single time with the rest of the observations?

- At day 51 the double source was observed at 15.4 GHz but not at 22.2 GHz. This may happen if the sensitivities differ, or if the CBs have different spectra, as they should (they have different parameters and they are crossing inhomogeneities at a given distance at different observer's times and slightly different angles).
- The predicted angular distances between the CBs at days 3 and 8 are unresolvably small, particularly if they are corrected by the factor $(0.28 \pm 0.5)/0.35$ discrepancy between the observation and the prediction, see Fig. (2b).
- Similarly corrected, the predicted inter-CB angles at days 25 and 83 are $\sim 0.22 \pm 0.04$ mas and $\sim 0.34 \pm 0.06$ mas, which should have been resolvable. The slower CB must strongly dominate the fluence at these dates. This is perfectly compatible with the CBs' rebrightening history, summarized in Fig. (2a): at day 25 the slower CB has recently rebrightened, and it is the only one observed. At day 51 the faster CB is strongly rebrightening, it is the extra source. After a very intense rebrightening the fluence decreases fast, and by day 83 the faster CB has faded out of sight.

Two other items must be explained: the proper-motion limits of Eq. (2), to be discussed in §5, and the "source sizes" cited in §2. The sizes of astronomical ejecta may appear to be very different at different wavelengths. An example is the radio galaxy Pictor A. Observed in X-rays by Chandra, it shows a non-expanding jet that emanates from the centre of the galaxy and extends across ~ 110 kpc towards a brilliant hot spot ~ 250 kpc away (Wilson, Young & Shopbell 2001). Observed at 1.4 GHz with VLA (Grandi et al. 2003) the diametrically opposed jets have a somewhat biconical shape, with a large lateral extension. In Dar & De Rújula (2003a) we have argued that the extensive radio image is due to electrons that the CBs of Pictor A have bounced in their voyage and "non-collisionally" accelerated to "cosmic-ray" energies. These electrons may have high energies, but their synchrotron radiation is only visible in radio, given the low value of the intergalactic magnetic fields. Contrariwise, synchrotron radiation by electrons within a CB's much larger field produces photons of much higher energy, originating from a very much more localized source.

Observations such as the above one imply that the CBs of GRBs, though effectively "point-like" in their visible or X-ray emission, may be "sizeable" in the radio. The sizes observed by TFBK may be the sizes of the CB-induced forward cone of electrons, not of the CBs themselves. These sizes may have a complicated time dependence, since they are functions of the ambient densities and magnetic fields that the CBs encounter.

5. Proper motion limits on the CB model

TFBK state: *"Dar & De Rújula (2003b) predicted a displacement of 2 mas over the 80 days of our VLBI experiment assuming plasmoids propagating in a constant density medium. This estimate was revised downward to 0.55 mas by incorporating plasmoid interactions with density inhomogeneities at a distance of ∼100 pc within a wind-blown medium (Dado, Dar & De Rújula 2004). Neither variant of this model is consistent with our proper motion limits."*

TFBK are right in stating that the DDD prediction for the motion of a *single* source is not what is observed[3], though it is difficult to rule out a proper motion with confidence with data containing 20σ evidence for two sources separated by 28 mas. This datum and the proper-motion limits are inconsistent at first sight. If the radio luminosity of the slower CB dominates the radio AG after its rebrightening, there is no contradiction with the proper

[3]The proper-motion limit in Eq. (2) is, strictly speaking, not a test of the proper motion predicted by the CB model. This is because TFBK presumably tested the hypothesis of a displacement $\vec{d} = \vec{v}\, t$, with $\vec{v}$ a constant. In the CB model, CBs decelerate and the prediction is, as in Eq. (3), $\vec{d} \approx \vec{w}\, t^{1/3}$ with $\vec{w}$ a constant vector (DDD). Given the relatively large error bars, this point may be minor.

motion limit, as shown in Fig. (2a). The limit refers to a single source, the central value of the circular-Gaussian fits to the data. In our interpretation, that source is the slow CB.

6. Scintillations

TFBK state: *"Strong and persistent intensity variations in centimeter radio light curves for* **all** *GRBs are expected in the cannonball model. Strong intensity variations are not seen for GRB 030329 ... There are moderate variations seen in the radio light curves of GRB 030329 (25% at 4.9 GHz, 15% at 8.5 GHz and 8% at 15 GHz) which decrease by a factor of three from* $\sim$*3 to 40 d after the burst."* That *"strong intensity variations are not seen"* is, we believe, an overstatement. The radio light curves (Sheth et al. 2003; Berger et al. 2003) show intensity variations that at 4.86 GHz are close to a factor of 2 through day 10.

The observed trend of intensity variations diminishing with time can be understood within the CB model (Dado et al. 2003a, DDD). They are very reminiscent of the ones seen in radio signals from pulsars in the Galaxy. Gupta (1995) demonstrated for a sample of 59 pulsars that their transverse speed, V_{iss}, measured from their interstellar scintillations, agrees well with the value, V_{pm}, directly measured as proper motion (see also Nicastro et al. 2001). The mean V_{pm} of Gupta's pulsars is 311 $\mathrm{km\,s^{-1}}$ and their mean distance $\langle D\rangle$ is $\sim$ 1.96 kpc. Their angular speeds are within an order of magnitude of a central value $\dot\alpha_{pm} = \langle V_{pm}\rangle/\langle D\rangle \simeq 5.1\times10^{-15}$ rad $\mathrm{s^{-1}}$. Such angular velocities result in observed scintillations *"with a modulation index of order unity and a time scale of a few hours"* (TFBK).

The predicted angular velocities of the CBs can be estimated with use of Eq. (4) and the effective x_∞ values quoted in Section 3. They are $\dot\alpha_{\rm CB}\sim 1.7\times10^{-15}$ rad $\mathrm{s^{-1}}$ and $\sim 8.6\times10^{-16}$ rad $\mathrm{s^{-1}}$ for the faster and slower CB at day 3. These are somewhat smaller than the typical pulsar values and should result in the observed *"modulation index of order unity and time scale of a few hours"* at the smaller VLBI radio frequencies. On day 40, the other date chosen by TFBK in discussing scintillations, the predictions are $\dot\alpha_{\rm CB}\sim 2.9\times10^{-16}$ rad $\mathrm{s^{-1}}$ and $\sim 1.4\times10^{-16}$ rad $\mathrm{s^{-1}}$ for the faster and slower (dominant) CB. These values are more than one order of magnitude smaller than the typical pulsar values. By then, the expected scintillations should be similar to those observed in very slowly moving pulsars, which are mainly due to the motions of the Earth, the Sun and the turbulent interstellar medium. Their modulation index is far below unity and their time scale is days long. This evolution towards less pronounced scintillations is precisely the trend of the GRB 030329 data. For this reason, we do not agree with TFBK that the absence of rapid fluctuations is a problem for the CB model.

We gave an explanation in Dar & De Rújula (2003a) why the observed jets of CBs are wider in radio than at higher frequencies, and extracted here the consequence that the CBs of GRBs may have observable radio sizes (§4). A size increasing with time would progresively quench scintillations, as in standard models (Frail et al. 1997).

7. Conclusions

TFBK conclude: *"Much less easy to explain is the single observation 51 days after the burst of an additional radio component 0.28 mas northeast of the main afterglow. This component requires a high average velocity of* $19\,c$ *and cannot be readily explained by any of the standard models. Since it is only seen at a single frequency, it is remotely possible that this image is an artifact of the calibration."*

We have interpreted the double source discovered by TFBK as an image of the two cannonballs required in the CB model to explain the double-peaked shape of GRB 030329 and the double-shoulder nature of its optical AG. The observed separation between the CBs is roughly the separation expected from the CB-model fit in DDD to the optical AG of GRB 030329. But the main point is that the two CBs appear to have been observed, and their separation is "hyperluminal". Seen in this light, the double source observed by TFBK is an extraordinarily important discovery in GRB physics, rather than a 20σ fly in the ointment.

Acknowledgements. We are grateful to Greg Taylor for having sent us a poster containing a preliminary version of the TFBK results, and for useful discussions on version 1 of this paper. We are indebted to Andy Cohen and Shelly Glashow for useful comments and suggestions. This research was supported in part by the Helen Asher Space Research Fund and by the VPR fund for research at the Technion.

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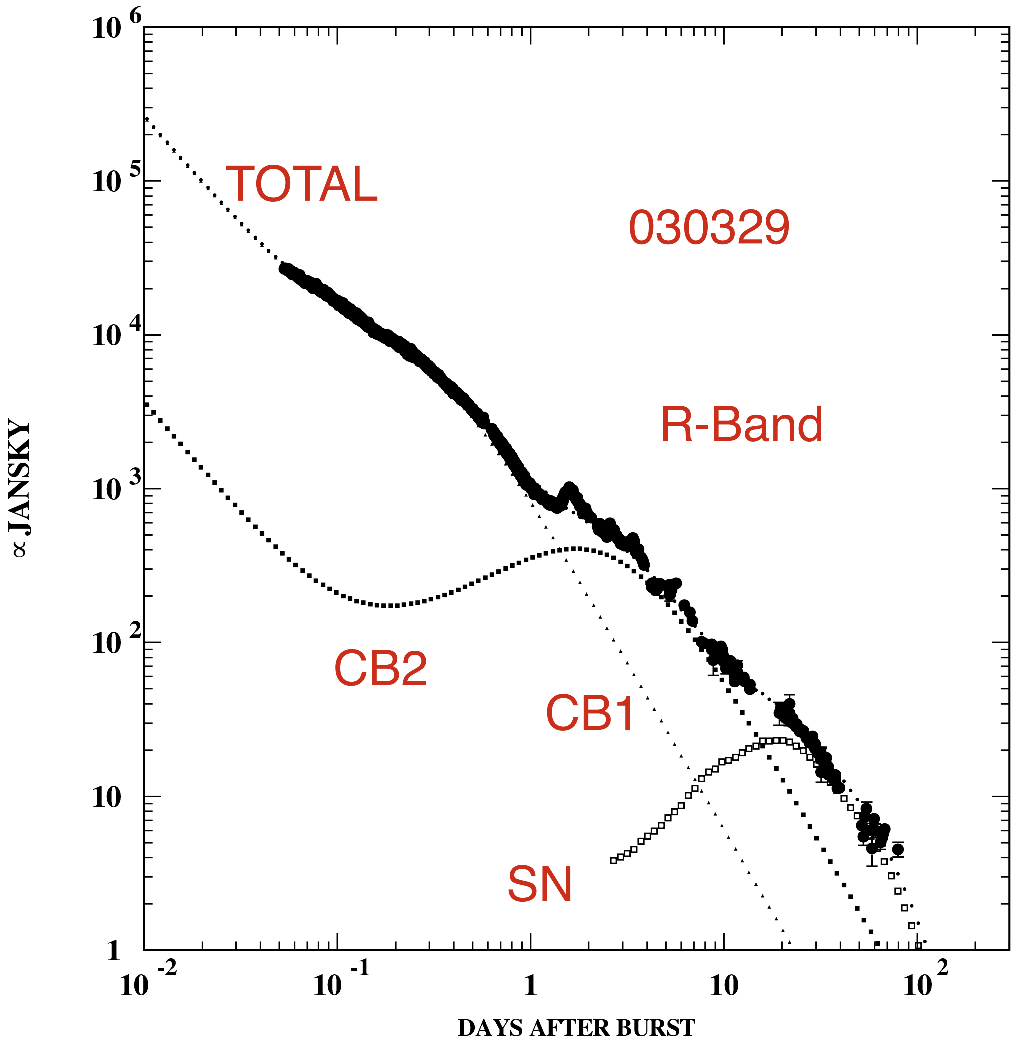

Fig. 1.— The R-Band AG of GRB 030329 fit in the CB model with a constant-density ISM and two CBs (DDD and references therein).

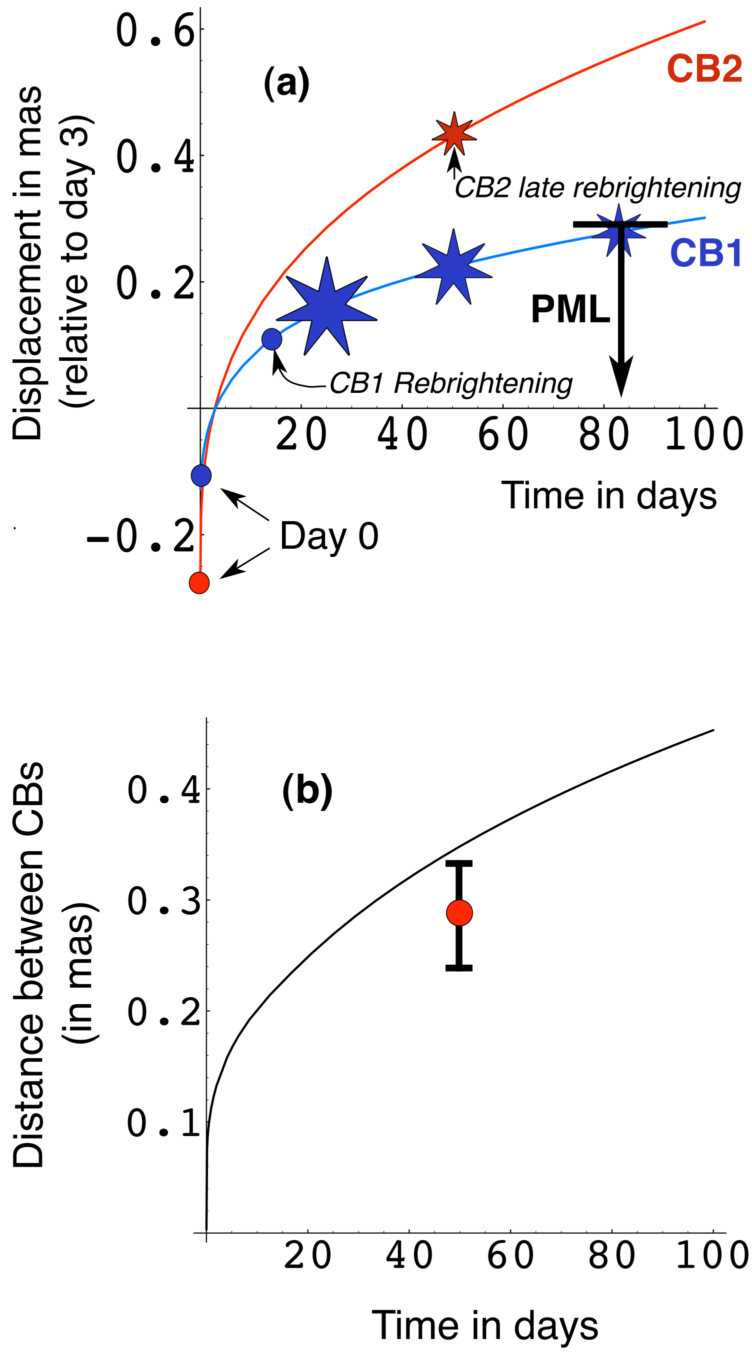

Fig. 2.— **(a)** The predicted angular displacement in the sky (in mas) of the two CBs of GRB 030329, as a function of observer's time from the first day of radio observations, day ~ 3. The positions at day 0, the start-up time of the successive predicted rebrightenings of the slower CB1, the observed time of the intense late rebrightening of the faster CB2, as well as the fluences at 15.3 GHz on day 51 (70% and 30% of the total) are illustrated. The proper motion limit (PML) of TFBK is also shown, and discussed in Section 5. **(b)** The predicted angular distance between the two CBs as a function of time, and its TFBK measurement at day 51, Eq. (1).